

APPARATUS AND METHODS FOR MODULATING REFRACTIVE INDEX

Cross-Reference to Related Applications

[0001] This application claims the benefit of U.S. provisional application No. 60/421,617, filed 5 October 25, 2002, which is hereby incorporated by reference herein in its entirety.

Background of the Invention

[0002] The present invention relates to apparatus and methods for modulating refractive index. More particularly, the invention relates to inducing a change of refractive index in one or more layers of an ionic-refractive structure that are capable of ion intercalation or release. The ion intercalation or release is accompanied by a change of refractive index without a significant increase in the optical absorption at the wavelength of interest or at the operating wavelength. The structure may be suitable for the fabrication of or integration with tunable optical filters, wavelength-selective optical elements, active modulated interferometers, variable phase shifters, sensors, lenses, and other optical components.

[0003] Various approaches have been employed for modulating refractive index in a wide range of optical devices including interferometric optical waveguide-based switches, light detection and ranging (LIDAR) 5 remote sensors, optical Doppler Tomography, filters for optical communications, and instruments to detect displacement. In most instances, modulating refractive index involves application of a voltage across a liquid crystal film, or across an electro-optical film, such 10 as lithium niobate, or through carrier induced refractive index changes in, for example, gallium arsenide (GaAs). Elasto-optic, magneto-optic, and acousto-optic effects can also provide a change in refractive index.

[0004] It has been shown that the refractive index 15 of many semiconducting metal oxides depends on the degree of intercalation of ions entering the matrix -- i.e., the extent to which ions are inserted into the metal oxide. For example, the real and imaginary 20 portions of the refractive index of tungsten oxide at 550 nm change significantly as lithium ions are inserted into the tungsten oxide (Rubin et al., "Optical Indices of Lithiated Electrochromic Oxides," in Lawrence Berkeley National Labs Publication 39410 25 (1996)). As described by Rubin, the real portion of the refractive index changes from 1.95 to 1.7 after ion intercalation while the imaginary portion of the refractive index changes by 0.1. At longer wavelengths, there may be little or no change of the 30 real portion of the refractive index as the imaginary portion of the refractive index changes from an extinction coefficient of 0 to 0.65.

[0005] Meanwhile, a considerable change in the refractive index of sputtered tungsten oxide with lithium ion insertion has been observed in the 2 micron to 12 micron wavelength range (Hutchins et al., 5 "Infrared Reflectance Modulation in Tungsten Oxide Based Electrochromic Devices," Electrochemica Acta, Vol. 46, at 1983-1988 (2001)). Such a change in refractive index of tungsten oxide could be used to create a front surface reflectance device (Hutchins et 10 al., "Electrochromic Tungsten Oxide Films for Variable Reflectance Devices," Proceedings of the SPIE, Vol. 4458, at 138-145 (2001)).

[0006] This follows in part from the relationship between the real portion of the dielectric constant, ϵ_r , 15 determined by the phase velocity, and the imaginary portion of the dielectric constant, ϵ_i , determined by the absorption. The dielectric constant is also proportional to the square of the refractive index, thus the refractive index also has a real portion and 20 an imaginary portion. It is well known from the Kramers-Kronig equation that the real portion of the dielectric constant can be expressed as an integral of the imaginary portion.

$$\epsilon_r(\omega_0) = 1 + \frac{2}{\pi} \cdot P \int_0^\infty \frac{\omega \cdot \epsilon_i(\omega)}{\omega^2 - \omega_0^2} d\omega$$
$$\epsilon_i(\omega_0) = -\frac{2}{\pi} \cdot P \int_0^\infty \frac{\omega_0 \cdot (\epsilon_r(\omega) - 1)}{\omega^2 - \omega_0^2} d\omega$$

25 where ω is the complex angular frequency, ω_0 refers to the frequency of an optical transition, and P is the principal value of the integral. It should be noted 30 that the Kramers-Kronig equation may not be completely

valid for thin films (Leveque et al., "Ellipsometry on Sputter-Deposited Tin-Oxide Films: Optical Constants Versus Stoichiometry, Hydrogen Content, and Amount of Electrochemically Intercalated Lithium," Applied Optics, Vol. 37, at 7334-7341 (1990)).

[0007] However, many of these approaches that provide a change in refractive index are based on the alteration of the extinction coefficient, density, or coloration of their respective devices. Such approaches are described, for example, in Lach et al. U.S. Patent No. 6,498,358. Moreover, while each of these approaches provides some change in refractive index, these approaches generally suffer from high manufacturing costs, constraints on the operating environment (e.g., temperature and pressure), and drawbacks related to system and substrate compatibility. Even further, many of these approaches significantly change the transmissivity while changing the refractive index, thereby limiting the applicability of the device.

[0008] It would therefore be desirable to provide apparatus and methods for modulating refractive index without significantly altering the transmissivity.

[0009] It would also be desirable to provide apparatus and methods for modulating refractive index that is easily integrated with optical components.

[0010] It would also be desirable to provide apparatus and methods for modulating refractive index via the insertion of an ionic species into an intercalating metal oxide without significantly altering the transmissivity of the metal oxide.

Summary of the Invention

[0011] In accordance with this invention, a thin film structure that is capable of ion intercalation or release, where the ion intercalation or release is
5 accompanied by a change of refractive index without significant optical absorption at the wavelength of interest or at the operating wavelength is provided. The thin film structure is referred to herein as an
10 "iono-refractive structure" because it includes one or more ion insertion layers having a real portion and an imaginary portion of the dielectric constant. While both the real portion and the imaginary portion of the dielectric constant change, the change in the imaginary portion is either less than the change in the real
15 portion or limited to acceptable values specific to the operation of a particular device at the wavelength of interest or at the operational wavelength. The iono-refractive structure may be suitable for the
20 fabrication of or integration with tunable optical filters, wavelength-selective optical elements, active modulated interferometers, variable phase shifters, sensors, lenses, and other optical components.

[0012] The iono-refractive structure may include an ion conduction layer and an ion insertion layer. The
25 ion conduction layer is preferably a material selected for its compatibility with the ion insertion layer. Ion conduction layer may be a layer of metal oxide, such as, for example, lithium phosphorous oxynitride, lithium aluminium fluoride, lithium phosphate, or
30 lithium orthophosphate, lanthanum lithium titanate. The ion insertion layer is preferably a metal oxide, such as vanadium pentoxide or $\text{Li}_2\text{O}-\text{P}_2\text{O}_5-\text{WO}_3$, deposited on the surface of the ion conduction layer.

[0013] In response to the application of an electric field across the ion insertion layer and the ion conduction layer, ions are inserted from the ion conduction layer to the ion insertion layer. In some 5 embodiments, an ion storage layer may be provided that store ions for transport across the ion conduction layer and into the ion insertion layer. The response to inserting ions into the ion insertion layer includes a change in both the real portion and the imaginary 10 portion of the dielectric constant. The change in the imaginary portion of the dielectric constant is less than the change of the real portion of the dielectric constant at the wavelength of interest or at the operational wavelength.

15 [0014] The change in the dielectric constant may be reversed. Ions may be extracted from the ion insertion layer back to the ion conduction layer. Subjecting the ion insertion layer to these conditions may lead to cases which result in a change of the imaginary portion 20 of the dielectric constant to a value that is within 2% of the initial imaginary portion and a change of the real portion of the dielectric constant to a value that is within 2% of the initial real portion.

[0015] In some embodiments, the iono-refractive 25 structure may be included in embodiments where the beam of light enters perpendicular to the plane of the device (e.g., wavelength filters, Fabry-Perot interferometers, multiple layer dielectric coatings, laser external cavities, etc.). In other suitable 30 embodiments, the iono-refractive structure may be include in embodiments where the light beam propagates along the plane of the device (e.g., by an external coupler or generated by a laser or a light-emitting

diode coupled directly to an optical waveguide). Such embodiments may include, for example, active interferometers, Fourier Transform Interferometers (FTIR), lenses with variable focal length, and various 5 communications devices.

Brief Description of the Drawings

[0016] The above and other objects and advantages of the invention will be apparent upon consideration of 10 the following detailed description, taken in conjunction with accompanying drawings, in which like reference refers to like parts throughout, and in which:

[0017] FIG. 1 is a cross-sectional view of an iono-refractive structure in accordance with various 15 embodiments of the present invention;

[0018] FIG. 2 shows an illustrative tunable Fabry-Perot etalon filter that has an iono-refractive structure in accordance with various embodiments of the 20 present invention; and

[0019] FIGS. 3A-3F show illustrative optical waveguide structures that may be controlled by an iono-refractive structure in accordance with various 25 embodiments of the present invention.

Detailed Description of the Invention

[0020] The present invention involves thin film structures. For convenience herein, these thin film structures are sometimes referred to as "iono-refractive structures" or "iono-refractive circuits" 30 because they include one or more ion insertion layers having a real portion and an imaginary portion of the dielectric constant. While both the real portion of

the dielectric constant and the imaginary portion of the dielectric constant change, the change in the imaginary portion is either less than the change in the real portion or limited to acceptable values specific
5 to the operation of a particular device at the wavelength of interest or at the operational wavelength.

[0021] FIG. 1 illustrates schematically, in cross section, a portion of an iono-refractive structure 100 which may be relevant to or useful in connection with
10 certain embodiments of the present invention. Structure 100 includes a substrate 102, a first electrode layer 104, an ion conduction layer 106, an ion insertion layer 108, and a second electrode
15 layer 110.

[0022] As used herein, the term "layer" refers to any suitable layer, region, film, or any other variation thereof, deposited using any suitable technique.

20 [0023] In accordance with some embodiments, structure 100 may also include an ion storage layer 112 positioned between first electrode layer 104 and ion conduction layer 106. Structure 100 may also include an interface layer 114 at the interface between the ion
25 conduction layer 106 and the ion insertion layer 108. As will be explained more fully below, interface layer 114 helps in maintaining uniform and accelerated ion flow from ion storage layer 112 or ion conduction layer 106 into ion insertion layer 108.

30 [0024] In some embodiments, substrate 102 may be substantially transparent. Substrate 102 may be a glass substrate, a polymeric substrate, or any other suitable substrate that is substantially transparent.

In other embodiments, substrate may be a reflective, opaque, or partially transparent substrate.

Substrate 102 may also take the form of nonplanar complex shapes, patterns, arrays or designs.

5 [0025] First electrode layer 104 and second electrode layer 110 are preferably conductive oxide layers that are substantially transparent. Although first electrode layer 104 and second electrode layer 110 are generally described herein as being substantially transparent, this embodiment is not limited only to substantially transparent conductive oxide electrodes. Rather, first electrode layer 104 and/or second electrode layer 110 may be reflective, opaque, or partially transparent. Materials that are 10 suitable for first electrode layer 104 and second electrode layer 110 include, for example, indium tin oxide (ITO), fluorine-doped tin oxide (SnO₂:F), antimony-doped tin oxide (SnO₂:Sb), members of the family In₂O₃-Ga₂O₃-ZnO, any other suitable metals, and 15 any other suitable electrically conductive materials. 20 In some embodiments, first electrode layer 104 and second electrode layer 110 may be formed in nonplanar complex shapes, patterns, arrays or designs to control distributions of indexes of refraction. First electrode layer 104 and second electrode layer 110 may 25 be formed to produce a uniform change in the refractive index or a spatially non-uniform distribution in the index of refraction.

[0026] Ion conduction layer 106 is preferably a 30 material selected for its compatibility with the overlying ion insertion layer 108. Materials that are suitable for ion conduction layer 106 include lithium phosphorous oxynitride, lithium aluminium fluoride,

lithium phosphate, lithium orthophosphate, lanthanum lithium titanate, and families of materials of the composition $\text{Li}_2\text{O}-\text{P}_2\text{O}_5-\text{[A}_\text{b}\text{O}_\text{x}\text{]}$, where $\text{A}_\text{b}\text{O}_\text{x}$ may be WO_3 , TiO_2 or Fe_2O_3 , or any appropriate combination thereof.

5 Generally, these materials are metal oxides that include lithium. In some embodiments, the thickness of ion conduction layer 106 is substantially thin to minimize the required electric field for transporting ions across ion conduction layer 106 -- i.e., a thin 10 ion conduction layer 106 reduces the transit time of ions across ion conduction layer 106. Typically, ion conduction layer 106 has a thickness less than about 0.10 microns.

[0027] Ion insertion layer 108 is preferably a metal oxide deposited on the surface of ion conduction layer 106. Ion insertion layer 108 is preferably selected for its capability of being intercalated with ions. Materials that are suitable for ion insertion layer 108 include oxides of tungsten, niobium, 20 vanadium, cerium, titanium, molybdenum, nickel, and cobalt. In some embodiments, the ion insertion layer is $\text{Li}_2\text{O}-\text{P}_2\text{O}_5-\text{WO}_3$, in which the P_2O_5 composition is about 30% to about 50% of the layer by weight, the WO_3 composition is about 20% to about 30% by weight, and the Li_2O composition is the remainder of the layer by weight. In another suitable approach, the ion 25 insertion layer is vanadium pentoxide. When ion insertion layer 108 is vanadium pentoxide, ion insertion layer 108 preferably has a thickness in the range of about 0.25 microns to about 0.6 microns. The ion insertion layer may be deposited by thermal evaporation, electron beam evaporation, chemical vapor deposition, plasma enhanced chemical vapor deposition,

magnetron sputtering, ion sputtering, sol-gel deposition, co-deposition with polymeric or transition metal oxide materials, deposition from a melt, or any other suitable approach.

5 [0028] It should also be noted that for optimal use of many of the embodiments described herein may require that ion insertion layer 106 and ion storage layer 108 do not substantially change color (transmissivity) upon oxidation or reduction processes.

10 [0029] Ion storage layer 112 is preferably a material selected for its compatibility with the overlying ion conduction layer 106 and ion insertion layer 108. Materials that are suitable for ion storage layer 112 include cerium oxide, cerium oxide-titanium oxide having a low titanium or a low cerium concentration, cerium vanadate, iron vanadate, cerium oxide-tin oxide, cerium oxide-zirconium oxide, cerium/antimony tin oxide, antimony/tin oxide, molybdenum/tin oxide, indium orthovanadate, tin oxide, 20 iron/vanadium oxide (1:9), iron/titanium oxide, and iron/nickel oxide. When ion storage layer 112 is tin oxide, ion storage layer 112 preferably has a thickness of about 0.25 microns.

[0030] Ion storage layer 112 stores ions for transport across ion conduction layer 106 and into ion insertion layer 108. Furthermore, it should be noted that the transmissivity of ion storage layer 112 does not substantially change upon ion egress or ingress. It should also be noted that ion storage layer 112 may 30 be deposited to prevent unwanted electrochemical reactions -- e.g., the electrolysis of water.

[0031] Interface layer 114 may contribute to uniform ion flow. In some embodiments, interface layer 114 is

deposited via co-depositing polyoxometalate or any other suitable first ion conduction cluster as a continuous phase across the boundary between ion conduction layer 106 and ion insertion layer 108 while 5 simultaneously depositing a second ion conduction cluster that is less conducting than the first ion conduction cluster.

[0032] In response to the application of an electric field across first electrode layer 104 and second 10 electrode layer 110, ions are inserted from ion conduction layer 106 to ion insertion layer 108. If ion storage layer 112 is present, ions may also be inserted from ion storage layer 112 across ion conduction layer 106. It should also be noted that the 15 insertion of ions into ion insertion layer 108 is reversible. The ions may also be extracted from ion insertion layer 108 and inserted back into ion conduction layer 106, thereby reversing the process.

[0033] However, it should be noted that ions may be 20 inserted into or extracted from ion insertion layer 108 using any other suitable approach. For example, instead of applying an electric field, ions may be inserted into ion insertion layer 108 via an electrochemical reaction.

[0034] It should also be noted that iono-refractive 25 structure 100 having a vanadium pentoxide ion insertion layer 108 and a tin oxide ion storage layer 112 is especially advantageous because the refractive index of vanadium oxide and the refractive index of tin oxide 30 change in opposite directions upon lithium intercalation.

[0035] Referring back to the Kramers-Kronig equation, the dielectric constant of a material has a

real portion and an imaginary portion. Typically, the response to inserting ions into ion insertion layer 108 includes a change in both the real portion and the imaginary portion of the dielectric constant. However,

5 subjecting the ion insertion layer to certain conditions may lead to cases which result in a change of the imaginary portion of the dielectric constant ($\Delta\epsilon_i$) that is less than the change of the real portion of the dielectric constant ($\Delta\epsilon_r$) at the wavelength of

10 interest or at the operation wavelength. Some embodiments may include interaction of ion insertion layer 108 with light at a wavelength having an energy that is considerably less than the bandgap (E_g) -- i.e., sub-bandgap energy.

15 [0036] The change in the dielectric constant may be reversed. For example, ions may be extracted from the ion insertion layer back to the ion conduction layer. This may result in a change of the imaginary portion of the dielectric constant to a value that is within 2% of

20 the initial imaginary portion of the dielectric constant and a change of the real portion of the dielectric constant to a value that is within 2% of the initial real portion of the dielectric constant.

[0037] Some embodiments may include selecting the

25 ion insertion layer and the ion storage layer from materials that are weakly electrochromic. More particularly, a material is strongly electrochromic when the availability of multiple valence states of the ion insertion layer permits the localization of charge

30 on a transition metal site that can be transferred to a neighboring site upon photon absorption -- i.e., the small polaron effect. That is, the optical absorption of the ion insertion layer is caused by electron

exchange between adjacent transition metal sites. For example, when the ion insertion layer is tungsten oxide (WO_3), electrochromism is caused by reduction of W^{6+} states to W^{5+} states upon ion insertion -- i.e., small 5 polaron transitions between two nonequivalent sites of tungsten (W^{5+} and W^{6+}). The inserted electrons are localized in W^{5+} sites and polarize their surrounding lattice to form small polarons. Incident photons are absorbed by these small polarons that hop from one site 10 to another. The enhancement in the absorption of oxygen deficient WO_3 is thought to relate to polarons hopping between W^{4+} and W^{5+} states.

[0038] Some embodiments in which the change of the imaginary portion of the dielectric constant is less 15 than the imaginary portion of the dielectric constant may also include a structural transition of the lattice of the ion insertion layer. A structural transition of the lattice provides a change in the refractive index with minimal change in transmissivity. In some 20 embodiments, the change of the lattice structure may accompany lattice expansion or contraction during ion insertion. In other embodiments, a change in lattice structure may result from a thermally-induced lattice expansion or contraction or from following an ion 25 insertion process with an ion implantation process.

[0039] Some embodiments may include thermal annealing the ion insertion layer in an oxygen atmosphere. WO_3 can be bleached by heating the layer in an oxygen atmosphere. Similarly, a WO_3 film fabricated 30 in a high oxygen environment may exhibit reduced coloration efficiency. Thus, annealing the ion insertion layer causes the change in absorption to be diminished. This occurs through reduction of effects

associated with polaron hopping between W⁴⁺ and W⁵⁺ states.

[0040] Some embodiments may include alloying the ion insertion layer with other molecular constituents not providing a small polaronic effect in the wavelength range in which the device operates (such as cerium oxide, tin oxide, vanadium oxide, and any appropriate combinations thereof). As used herein, the term "color center" is used to describe a location of trapped electrons or holes within a metal oxide lattice that gives rise to optical absorption through interaction with incident light. For example, electrons trapped at metal ion sites, such as W⁶⁺ in WO₃ or Ti⁴⁺ in TiO₂, exhibit a broad absorption peak in the infrared and the near infrared spectral range. The number or strength of color centers induced by ion insertion or removal in the ion insertion layer is diminished through alloying.

[0041] Some embodiments may include material constituents that diminish the change in optical absorption accompanying ion insertion. This may be accomplished by adding cerium, tin, zirconium, or other metals having oxides that do not lead to significant electrochromic reactions.

[0042] However, any other suitable approach for providing a desirable ratio of $\Delta\epsilon_i/\Delta\epsilon_r$ may also be used. In some embodiments, $\Delta\epsilon_i/\Delta\epsilon_r$ less than 1.5. In some embodiments, $\Delta\epsilon_i/\Delta\epsilon_r$ is less than about 0.4. That is, iono-refractive structure 100 is operating at a sub-bandgap wavelength and away from optical absorbance transitions.

[0043] The following non-limiting, illustrative examples illustrate various combinations of materials useful in structure 100 in accordance with various

alternative embodiments. These examples are merely illustrative, and it is not intended that the invention be limited to these illustrative examples.

[0044] These various alternative embodiments may be 5 separated into three groups: embodiments where the beam of light enters perpendicular to the plane of the device, embodiments where the light is coupled to the device -- i.e., propagates along the plane of the device, and a combination of the two.

10 [0045] In embodiments where the beam of light enters perpendicular to the plane of the device, the iono-refractive structure may be used for wavelength filtering. Wavelength filters may be useful for fabricating apparatus and structures, such as Fabry- 15 Perot interferometers, multiple layer dielectric coatings, and laser external cavities.

[0046] In one embodiment, the iono-refractive structures may be used to fabricate a Fabry-Perot etalon. A Fabry-Perot etalon is the simplest form of a 20 Fabry-Perot interferometer. Generally, a Fabry-Perot etalon makes use of multiple reflections between two closely spaced partially mirrored surfaces. The etalon may have dielectric material of a given index of refraction and a given thickness. A portion of the 25 light is transmitted each time the light reaches the mirrored surface, thereby resulting in multiple offset beams which can interfere with each other. The accumulating number of interfering beams produces an interferometer with high resolution. The etalon may be used as a tunable filter by selecting the index of 30 refraction of the medium in the cavity to select a given resonant wavelength. Using the tunable Fabry-Perot etalon, the bandwidth of each transmission peak

is narrow and the given resonant wavelength is transmitted with maximum transmission.

[0047] In this embodiment, the iono-refractive structure may modulate the refractive index of one or 5 more coatings on the mirrored or glass plates that form the etalon. The tunable Fabry-Perot etalon may be used to develop a tunable narrow-band filter, which may be used in LIDAR detection, optical communications, or optical non-destructive evaluation (NDE).
10 [0048] The general equation for the transmission coefficient of an ideal Fabry Perot filter is:

$$\frac{I_\lambda}{I_{o\lambda}} = \frac{T(\lambda)^2}{[1 - R(\lambda)^2]} x \left\{ 1 + \left[\frac{2F(\lambda)}{\pi} \right]^2 \sin^2 \left[\frac{2\pi d \cos \theta}{\lambda} - \varepsilon(\lambda) \right]^{-1} \right\}$$

15 In this equation $T(\lambda)$ and $R(\lambda)$ are the wavelength dependent mirror transmission and reflectivity, respectively, and $F(\lambda)$ is the interferometer finesse. The full width half maximum (FWHM) pass-band of the Fabry-Perot filter with light impinging at vertical 20 incidence can be computed from the following equation:

$$\Delta\lambda = \frac{(1-R)\lambda_R^2}{2\pi d(R)^{1/2}}$$

25 where R is the mirror reflectivity, λ_R is the resonance wavelength, and d is the micro-cavity thickness. In some embodiments, the Fabry-Perot can be built as a free-standing device on one side of a substrate. Typically, the total thickness of the device is on the order of about 20 microns. For a micro-cavity 30 thickness of 20 microns, a mirror reflectivity of 0.99,

and a resonance wavelength of 1.08 microns, the FWHM is about 1.8 nm.

[0049] It should be noted that the parallelism of the Fabry-Perot filter is important to achieve the 5 highest throughput at a given stack thickness. Optical flats may be obtained with a parallelism of less than 3 arc minutes or better.

[0050] In another suitable approach, an optical flat may be used as a substrate. Optical flats may be 10 provided having a diameter of 50 mm, flatness of both surfaces to $\lambda/20$, and a surface quality of 60/40 scratch and dig. These surface flats have roughness on the order of about 0.5 nm. For a micro-cavity thickness of 1 mm, a mirror reflectivity of 0.99, and a 15 resonance wavelength of 1.08 microns, the FWHM is about 0.036 nm.

[0051] In one example, a vanadium pentoxide layer may be deposited along with a transparent conductive electrode, an ion conduction layer, such as $\text{Li}_2\text{O-P}_2\text{O}_5$, 20 and an ion storage layer, such as tin oxide, on one surface of the optical flat and partial mirrors on both surfaces of the optical flat. Depositing a thin film electrode on the free surface of the ion storage layer or the ion conduction layer (e.g., $\text{Li}_2\text{O-P}_2\text{O}_5$) as well as 25 on the surface of the ion insertion layer allows the application of an electric field across the ion insertion layer. The electric field drives (i.e., inserts) the lithium or hydrogen ions of the ion storage layer or the ion conduction layer into the ion 30 insertion layer (e.g., vanadium pentoxide layer), thereby altering the refractive index of the vanadium pentoxide while not substantially altering the transmissivity.

[0052] In operation, for example, an optical source component may be configured to generate light (e.g., photons) to pass through the Fabry-Perot apparatus. By illuminating the ion insertion layer (e.g., vanadium pentoxide) in the Fabry-Perot apparatus with a light having sub-bandgap energy, the real portion of the refractive index of the ion insertion layer preferably changes by more than about 0.1, while the imaginary portion of the refractive index of the ion insertion 5 layer preferably changes by less than about 0.2 in response to ion insertion by the application of an electric field. The wavelength of light illuminated passing through the ion insertion layer of the Fabry-Perot apparatus corresponds to a sub-bandgap energy, 10 where the sub-bandgap energy is between about 0.5 to about 0.75 of the bandgap of the ion insertion layer. By modulating the real portion of the refractive index 15 without substantially altering the imaginary portion (i.e., transmissivity), the ion insertion layer may be used as a tunable narrow-band filter. Such filters may 20 be used in LIDAR detection, optical communications, or optical non-destructive evaluation (NDE).

[0053] The change in refractive index of the vanadium pentoxide layer occurs at an electric field of 25 about 1.0 volts. However, it should be noted that since both vanadium pentoxide and $\text{Li}_2\text{O}\text{-P}_2\text{O}_5$ are sensitive to humid environments, an insulating protective thin film is preferably deposited over both layers. The insulating protective thin film is 30 preferably aluminum oxide.

[0054] FIG. 2 shows an illustrative tunable Fabry-Perot etalon filter in accordance with various embodiments of the present invention. As shown in

FIG. 2, the Fabry-Perot filter includes a substrate 220. Substrate 220 may be a glass substrate, a polymeric substrate, or any other suitable substrate. A dielectric stack 240 may be formed on the substrate 5 to form the first mirror of the Fabry-Perot filter. Dielectric stack 240 may include, for example, alternating layers of dielectric material to alter the reflectance of the Fabry-Perot filter. For example, dielectric stack 240 may include alternating layers of 10 tungsten oxide, lithium orthophosphate, and vanadium oxide. In another suitable example, dielectric stack 240 may include alternating layers of lithium orthophosphate and vanadium oxide.

[0055] A low-dielectric constant optically-transmissive spacer 260 may be provided on dielectric stack 240. As shown in FIG. 2, a zinc selenide (ZnSe) optical flat is provided. An iono-refractive structure 280 -- e.g., a vanadium oxide ion insertion layer, a $\text{Li}_2\text{O}-\text{P}_2\text{O}_5$ ion conduction layer, and a tin oxide ion storage layer -- may be formed on one or both sides 20 of spacer 22. Iono-refractive structure 260 may be used to select the center wavelength of interest. For example, by applying an electric field, ions are inserted from the ion conduction layer to the ion 25 insertion layer. The ion storage layer may also insert ions across ion conduction layer and into the ion insertion layer. The second mirror of the Fabry-Perot filter is formed by depositing another dielectric stack 240 on the iono-refractive structure 260.

[0056] The iono-refractive structure 260 may also include electrodes for applying the electric field to produce a uniform change in the refractive index or a spatially non-uniform distribution of the index of

refraction in the iono-refractive structure. Materials that are suitable for the electrodes include, for example, indium tin oxide (ITO), fluorine-doped tin oxide ($\text{SnO}_2:\text{F}$), antimony-doped tin oxide ($\text{SnO}_2:\text{Sb}$),
5 members of the family of $\text{In}_2\text{O}_3\text{-}\text{Ga}_2\text{O}_3\text{-}\text{ZnO}$, any other suitable metals, and any other suitable electrically conductive materials.

[0057] It should also be noted that the iono-refractive structure and the dielectric stack do not
10 change transmissivity while altering the bandwidth of the Fabry-Perot etalon.

[0058] In another embodiment, the iono-refractive structure may be used to fabricate multiple layer dielectric coatings. That is, a high reflectance
15 coating may be fabricated from multiple dielectric layers having alternating high refractive index and low refractive index thin films. The optical admittance can be represented a function of the refractive index of the high refractive index layer (n_H) and the low
20 refractive index layer (n_L).

$$Y = \left(\frac{n_H}{n_L} \right)^{2p} \frac{n_H^2}{n_S}$$

where n_S is the refractive index of the substrate and $(2p+1)$ is the number of layers in the dielectric stack.

[0059] In other embodiments where the beam of light
25 is transported in the plane of the device (e.g., by an external coupler or generated by a laser or a light-emitting diode coupled directly to the optical waveguide), the iono-refractive structure may be used to modulate the wavefront of a waveguide. This may be
30 used for fabricating apparatus, such as active interferometers, Fourier Transform interferometers (FTIR), a handheld FTIR, lenses with variable focal

length, and various communications devices. These devices may also be designed to alter the direction of the beam propagating in the waveguide or to provide a focus for the beam.

5 [0060] The variable refractive index layers may serve as electric field controlled optical waveguides. FIGS. 3A-3F show illustrative optical waveguide structures that may be controlled by an iono-refractive structure. The waveguides in FIGS. 3A-3F are

10 structures through which optical signals (i.e., light waves) propagate from a first location to a second location. As shown in FIGS. 3A-3F, waveguides may be in any convenient configuration and may include one or more straight segments, curved segments, or

15 combinations of both. FIGS. 3A-3F show an electroabsorption modulator, a Mach-Zehnder modulator, a directional coupler, an X coupler, an acoustooptic (diffraction) modulator, and a mode transformer (digital optical switch), respectively.

20 [0061] Each device shown in FIGS. 3A-3F has an iono-refractive structure 300 -- e.g., a vanadium pentoxide ion insertion layer, an ion conduction layer, a tin oxide ion storage layer, and a transparent electrically conductive oxide coated on a transparent substrate. In

25 some embodiments, iono-refractive structure 300 may be formed on a portion (e.g., a strip) of the waveguide. Upon applying an electric field across iono-refractive structure 300, the vanadium pentoxide ion insertion layer, ion conduction layer, tin oxide ion storage

30 layer and transparent electrically conductive oxide, a change in the refractive index of the waveguide occurs in the region of iono-refractive structure. This region of altered refractive index may be designed to

alter the direction of the beam propagating in the waveguide or provide a focus for the beam.

[0062] One application of the electric field controlled optical waveguide would be in the area of beam steering. In one suitable approach, light can propagate in an optical waveguide consisting of a vanadium pentoxide ion insertion layer, an ion conduction layer, a tin oxide ion storage layer, and a transparent electrically conductive oxide coated on a transparent substrate. In this example, the vanadium pentoxide layer has a thickness in the range of about 0.25 microns to about 0.6 microns. The ion conduction layer has a thickness of less than about 0.10 microns and the tin oxide ion storage layer has a thickness in the range of about 0.25 microns to about 0.6 microns. A circular electrode may be formed above the vanadium pentoxide ion insertion layer.

[0063] It should be noted that while this example discusses forming a circular electrode above the ion insertion layer, an electrode of any suitable shape may be formed. For example, electrodes having circular, rectangular, cylindrical, or elliptical shapes may be formed. Electrodes may also be formed using any suitable approach, such as, for example, electro-discharge machining (EDM), deposition and patterning, or conventional machining approaches.

[0064] Upon applying an electric field across the circular electrode, the vanadium pentoxide ion insertion layer, ion conduction layer, tin oxide ion storage layer and transparent electrically conductive oxide, a change in the refractive index of the waveguide occurs in the region of the circular electrode. This region of altered refractive index --

i.e., the region of the circular electrode -- may be designed to alter the direction of the beam propagating in the waveguide or provide a focus for the beam.

[0065] In several applications the iono-refractive structure may be formed at the surface of an optical waveguide. It should also be noted that the thickness of the ion insertion layer and one of the optically transparent, electrically conducting electrodes is preferably less than the depth of the evanescent field emanating from the waveguide surface.

[0066] In yet another embodiment, these electric field controlled optical waveguides may be used to fabricate devices useful in the area of Fourier transform interferometric spectral detection. In this embodiment, light entering the spectrometer passes through a beam splitter connected to two arms of the interferometer. The two arms of the interferometer meet at a location where constructive and destructive interference would take place. Modulation of the refractive index of one of the arms of the interferometer using ion insertion would result in a means of scanning the phase of the interferometer. This approach is useful in biophysical infrared modulation spectroscopy.

[0067] The iono-refractive structure may be used to develop a thin-film based phase-shifting interferometer. One or more multiple layered structures each having, for example, a transparent electrically conductive oxide layer, a vanadium pentoxide ion insertion layer, an ion conduction layer, a tin oxide ion insertion layer, and a transparent electrically conductive oxide, may be placed between two thin glass sheets to form a shear plate.

[0068] In yet another suitable embodiment, the iono-refractive structure may be integrated with a laser having a lasing mode right at the surface of the laser. The iono-refractive structure may be used to precisely 5 modulate the output wavelength, thereby creating a tunable laser using the iono-refractive structure.

[0069] It should be noted that in some of these 10 embodiments, the invention may include a controller (not shown) for calculating the change in refractive index with applied voltage and transferred ionic current. For example, when the iono-refractive structure is used as a wavelength filter, a controller may be provided that uses the change in refractive 15 index with applied voltage and transferred ionic current to determine variables, such as the electric field to be applied.

[0070] Thus, methods and apparatus for modulating 20 refractive index using an iono-refractive structure, where the change in the imaginary portion of the dielectric constant is less than the change in the real portion of the dielectric constant, are provided. Persons skilled in the art will appreciate that the 25 present invention can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation, and that the present invention is limited only by the claims which follow.